

On a possible manifestation of the four color symmetry Z' boson in $\mu^+\mu^-$ events at the LHC

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Abstract

The cross section of the $\mu^+\mu^-$ pair production in pp -collisions at the LHC is calculated with account of the Z' boson induced by the minimal four color quark-lepton symmetry ($MQLS$). The $\mu^+\mu^-$ invariant mass spectrum with account of the $MQLS$ Z' boson is analysed in dependence on the Z' mass. The mass region for the $MQLS$ Z' boson observable at the LHC is found in dependence on the significance and on the integrated luminosity.

Keywords: Beyond the SM; four color symmetry; Pati–Salam; Z' boson; LHC.
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The search for a new physics beyond the Standard Model (SM) is an actual field of the elementary particle physics now. The near start of LHC will essentially enlarge the possibilities for search for new physics effects and in this situation the extensions of SM predicting new effects at the LHC energies (such as supersymmetry, left–right symmetry, two Higgs model, etc.) acquire the special interest.

One of the possible variants of such new physics can be induced by the possible four color quark–lepton symmetry of Pati–Salam type treating leptons as the fourth color [1]. The immediate consequence of this symmetry is the prediction of the specific new gauge particles – vector or chiral gauge leptoquarks and one or two additional neutral Z' bosons. In particular case of the minimal unification with the SM by the gauge group

$$G_{new} = SU_V(4) \times SU_L(2) \times U_R(1) \quad (1)$$

($MQLS$ model [2,3]) the four color symmetry (described here by the vector color group $SU_V(4)$) predicts one vector leptoquark V^\pm with electric charge $\pm 2/3$ and one additional neutral Z' boson. The interactions of these gauge fields with fermions are defined by the group (1) and give the possibility to investigate quantitatively the effects of these particles in dependence on their masses. Below we concentrate our attention on the additional Z' boson predicted by the four color symmetry unified with SM by the minimal group (1).

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It should be noted that additional Z' bosons appear in many extensions of the SM. In dependence on the model the most stringent lower limits on Z' masses are of order $M_{Z_\psi}, M_{Z_\chi} > 0.822$ TeV [4] for Z' bosons of E_6 model from Z' direct searches at the Tevatron [5] and $M_{Z_{LR}} > 0.86$ TeV, $M_{Z'_{SM}} > 1.5$ TeV [4] for Z' bosons of LR model and of the model with SM coupling constants from the global electroweak analysis [6]. The most stringent mass limit for the MQLSM Z' boson can be extracted from the LEP leptonic cross section $\sigma_{\bar{l}l} = \sigma(e^+e^- \rightarrow \gamma, Z, Z' \rightarrow \bar{l}l)$ [3] and with account the LEP2 data [7] is of about

$$m_{Z'} > 1.4 \text{ TeV}. \quad (2)$$

It is interesting now to know what is the mass region in which the MQLSM Z' boson can be observable at future search for Z' at the LHC. The most clean sign of the Z' boson production at the LHC can be the possible excess of $\mu^+\mu^-$ events resulting from Z' decays into $\mu^+\mu^-$ pairs. The investigation of the $\mu^+\mu^-$ invariant mass spectrum and of its possible deviation from the SM prediction will give the possibility to detect the production of Z' or to set the new mass limit on its mass. So the analysis of the process $pp \rightarrow \gamma, Z, Z' \rightarrow \mu^+\mu^-$ at the LHC energy is of interest.

In the present paper we calculate the cross section of lepton-antilepton pair production in pp -collisions at the LHC with account of Z' -boson predicted by the the four color symmetry of type (1). We obtain and discuss the mass region in which this Z' can be discovered at the LHC in comparison with the other models (E_6, LRM, SSM [8,9]) also predicting Z' bosons.

Interactions of the neutral gauge bosons with the SM fermions can be written as

$$\mathcal{L}_{NC}^{gauge} = -|e| \sum_i J_\mu^i A_i^\mu, \quad (3)$$

where e is an electron charge, A_i ($i = 0, 1, 2$) denote the gauge boson γ, Z, Z' ,

$$J_\mu^i = \sum_{f_a} \bar{f}_a \gamma_\mu (v_{f_a}^i + \gamma_5 a_{f_a}^i) f_a \quad (4)$$

are the neutral currents and $v_{f_a}^i \equiv v_{f_a}^{A_i}$ and $a_{f_a}^i \equiv a_{f_a}^{A_i}$ are the vector and axial coupling constants of fermion f_a with gauge boson A_i (f is quark or lepton, $a = 1, 2$ for up and down fermion).

In general case the mass eigenstates Z and Z' are superposition of two basic fields Z_1 and Z_2 . With account of $Z - Z'$ mixing the coupling constants of Z and Z' with fermions can be written as

$$v_{f_a}^Z = v_{f_a}^{Z_1} \cos \theta_m - v_{f_a}^{Z_2} \sin \theta_m, \quad a_{f_a}^Z = a_{f_a}^{Z_1} \cos \theta_m - a_{f_a}^{Z_2} \sin \theta_m, \quad (5)$$

$$v_{f_a}^{Z'} = v_{f_a}^{Z_1} \sin \theta_m + v_{f_a}^{Z_2} \cos \theta_m, \quad a_{f_a}^{Z'} = a_{f_a}^{Z_1} \sin \theta_m + a_{f_a}^{Z_2} \cos \theta_m, \quad (6)$$

where

$$v_{f_a}^{Z_1} = \frac{(\tau_3)_{aa} - 4Q_{f_a}s_W^2}{4s_W c_W}, \quad a_{f_a}^{Z_1} = \frac{(\tau_3)_{aa}}{4s_W c_W} \quad (7)$$

are the SM coupling constants, θ_m is the $Z - Z'$ mixing angle, $s_W = \sin \theta_W$, $c_W = \cos \theta_W$, θ_W is the Weinberg weak mixing angle, τ_3 is the Pauli matrix, Q_{f_a} is electric charge of fermion f_a in part of $|e|$.

The interaction of Z_2 field with fermions depends on the origin of this field. In MQLS model the coupling constants $v_{f_a}^{Z_2}$, $a_{f_a}^{Z_2}$ have the form [10]

$$v_{f_a}^{Z_2} = \frac{1}{c_W s_S \sqrt{1 - s_W^2 - s_S^2}} [c_W^2 \sqrt{\frac{2}{3}} (t_{15})_f - (Q_{f_a} - \frac{(\tau_3)_{aa}}{4}) s_S^2], \quad (8)$$

$$a_{f_a}^{Z_2} = \frac{s_S}{c_W \sqrt{1 - s_W^2 - s_S^2}} \frac{(\tau_3)_{aa}}{4} \quad (9)$$

where t_{15} is the 15-th generator of $SU_V(4)$ group, $s_S = \sin \theta_S$ is the parameter of the model defined by relation of electromagnetic and strong coupling constants, θ_S is a strong mixing angle. In MQLS model the $Z - Z'$ mixing angle is small ($\theta_m < 0.006$) and we neglect below the $Z - Z'$ mixing believing $Z \approx Z_1$ and $Z' \approx Z_2$.

The differential cross-section of lepton-antilepton pair production in fermion-antifermion collision in the tree approximation is well known and for $m_f \ll \sqrt{s}$ can be written as [8,9]

$$d\sigma(\bar{f}_a f_a \xrightarrow{\gamma, Z, Z'} l^+ l^-) = \frac{\pi \alpha^2 s}{2N_c} \sum_{i,j} (2z B_{fal}^{ij} + (z^2 + 1) C_{fal}^{ij}) P_{ij}(s) dz. \quad (10)$$

Here α is the fine structure constant, s is the invariant mass square of the initial $\bar{f}f$ pair, $N_c = 1(3)$ denote colour factor for leptons (quarks), $z = \cos \theta$, θ is the scattering angle in the center of mass frame, $B_{fal}^{ij}, C_{fal}^{ij}$ are the combinations of the coupling constants of the form

$$C_{fal}^{ij} = (a_{fa}^i a_{fa}^j + v_{fa}^i v_{fa}^j)(a_l^i a_l^j + v_l^i v_l^j),$$

$$B_{fal}^{ij} = (a_{fa}^i v_{fa}^j + v_{fa}^i a_{fa}^j)(a_l^i v_l^j + v_l^i a_l^j),$$

$P_{ij}(s) = \text{Re}(P_i(s) P_j^*(s))$ and $P_i(s) = 1/(s - M_i^2 + iM_i \Gamma_i)$ is a factor coming from propagator of boson A_i with mass $M_i \equiv M_{A_i}$ and with width $\Gamma_i \equiv \Gamma_{A_i}$.

Integration of (10) over z gives the total cross-section in the form

$$\sigma(\bar{f}_a f_a \xrightarrow{\gamma, Z, Z'} l^+ l^-) = \frac{4\pi s \alpha^2}{3N_c} \sum_{i,j} C_{fal}^{ij} P_{ij}(s). \quad (11)$$

The differential cross-section of $\mu^+ \mu^-$ pair production in proton-proton collision (Drell-Yan process) with account of an additional Z' -boson can be written as

$$d\sigma(pp \xrightarrow{\gamma, Z, Z'} \mu^+ \mu^-) = \sum_k F_k(x_1, x_2, s) \sigma(\bar{q}_k q_k \xrightarrow{\gamma, Z, Z'} \mu^+ \mu^-) dx_1 dx_2 \quad (12)$$

where $s = x_1 x_2 S$, S is total energy square of colliding protons, $x_{1,2}$ is parton fraction of proton momentum and the function $F_k(x_1, x_2, s)$ can be expressed in the terms of parton distribution functions $f_{q_k}(x, s)$ ($f_{\bar{q}_k}(x, s)$) of k -flavor quarks q_k (antiquarks \bar{q}_k) as

$$F_k(x_1, x_2, s) = f_{q_k}(x_1, s) f_{\bar{q}_k}(x_2, s) + f_{\bar{q}_k}(x_1, s) f_{q_k}(x_2, s).$$

For the further analysis it is useful to go over from the variables $\{x_1, x_2\}$ to

$$M^2 = x_1 x_2 S, \quad y = \ln \frac{x_1}{x_2} \quad (13)$$

where M is invariant mass of quark-antiquark pair (which is equal to invariant mass of the final $\mu^+\mu^-$ pair), y is the final lepton rapidity, \sqrt{S} is the energy of colliding protons. In terms of the variables $\{M, y\}$ the cross section (12) takes the form

$$d\sigma(pp \xrightarrow{\gamma, Z, Z'} \mu^+\mu^-) = \frac{8\pi M^3 \alpha^2}{9S} \sum_k F_k\left(\frac{M}{\sqrt{S}}e^y, \frac{M}{\sqrt{S}}e^{-y}, M^2\right) \sum_{i,j} C_{q_k\mu}^{ij} P_{ij}(M^2) dM dy. \quad (14)$$

Integration of the cross section (14) over y gives the $\mu^+\mu^-$ invariant mass spectrum in the form

$$\frac{d\sigma(pp \xrightarrow{\gamma, Z, Z'} \mu^+\mu^-)}{dM} = \frac{8\pi M^3 \alpha^2}{9S} \sum_{i,j} I^{ij}(M, S) P_{ij}(M^2) \quad (15)$$

where

$$I^{ij}(M, S) = \sum_k I_k(M, S) C_{q_k\mu}^{ij}, \quad (16)$$

$$I_k(M, S) = \int_{-\ln \sqrt{S}/M}^{+\ln \sqrt{S}/M} F_k\left(\frac{M}{\sqrt{S}}e^y, \frac{M}{\sqrt{S}}e^{-y}, M^2\right) dy. \quad (17)$$

The analysis of the possible new effects in $\mu^+\mu^-$ invariant mass spectrum at the LHC was performed by CMS collaboration [11, 12]. This analysis is based on the statistical significance \mathcal{S}' estimation of the signal $pp \rightarrow \gamma, Z, Z' \rightarrow \mu^+\mu^-$ events in the presence of the background $pp \rightarrow \gamma, Z \rightarrow \mu^+\mu^-$ events, with Z' predicted by some models ($E_6, LRM, ALRM, SSM$).

There are different definitions of significance estimators in literature and we use here the next one [13]

$$\mathcal{S}' = \sqrt{2[(N_s + N_b) \ln(1 + N_s/N_b) - N_s]} \quad (18)$$

where N_s and N_b are number of signal and background events in the dilepton invariant mass region $M_{Z'} \pm \Delta M$. The numbers N_s and N_b can be calculated from the cross sections of type (15) as

$$N_s = L \sigma_s(M_{Z'}, \Delta M), \quad \sigma_s(M_{Z'}, \Delta M) = \int_{M_{Z'} - \Delta M}^{M_{Z'} + \Delta M} \frac{d\sigma(pp \xrightarrow{\gamma, Z, Z'} \mu^+\mu^-)}{dM} dM, \quad (19)$$

$$N_b = L \sigma_{SM}(M_{Z'}, \Delta M), \quad \sigma_{SM}(M_{Z'}, \Delta M) = \int_{M_{Z'} - \Delta M}^{M_{Z'} + \Delta M} \frac{d\sigma(pp \xrightarrow{\gamma, Z} \mu^+\mu^-)}{dM} dM \quad (20)$$

where $L = \int \mathcal{L} dt$ is the integrated luminosity, $\sigma_s(M_{Z'}, \Delta M)$ and $\sigma_{SM}(M_{Z'}, \Delta M)$ are the cross sections for the signal and background events in the mass region $M_{Z'} \pm \Delta M$. Here ΔM is a mass window chosen below as $\Delta M = 0.85 \Gamma_{Z'}$, which corresponds to the width of 2σ in the case of Gaussian distribution [14].

The $\mu^+\mu^-$ invariant mass spectrum (15) depends on the mass $M_{Z'}$ and on the width $\Gamma_{Z'}$ of Z' boson. The fermionic decays of Z' boson are defined by the coupling constants (6–9) and the corresponding partial widths of Z' boson decays to $f_a \bar{f}_a$ pairs for $m_{f_a} \ll M_{Z'}$ have the form

$$\Gamma(Z' \rightarrow f_a \bar{f}_a) = N_f M_{Z'} \frac{\alpha}{3} ((v_{f_a}^{Z'})^2 + (a_{f_a}^{Z'})^2) \quad (21)$$

where the color factor $N_f = 1(3)$ for leptons(quarks) $f = l(q)$.

In the case of the Higgs mechanism of the fermion mass generation the four color symmetry of type (1) in addition to the SM Higgs doublet predicts the new scalar doublets: the color octet of scalar gluon doublets $F_{ja}, j = 1, \dots, 8$, two color triplets of scalar leptoquark doublets $S_{a\alpha}^{(\pm)}, \alpha = 1, 2, 3$ and additional colorless scalar doublet Φ'_a as well as some other scalar fields (more details can be found in [15]). The analysis of the mass limits for the scalar doublets $F_a, S_a^{(\pm)}, \Phi'_a$ from S, T, U parameters of electroweak radiative corrections [16,17], from $K_L^0 \rightarrow e^\mp \mu^\pm$ and $B^0 \rightarrow e^\mp \tau^\pm$ decays [4,18,19], from the magnetic moments of muon [20] and of neutrino [21] showed that these scalar doublets can be light, with masses below 1 TeV. So, the MQLSM Z' boson can decay also into pairs of these scalar particles, which gives the additional to (21) contributions to Z' width.

Writing the interaction of Z' boson with scalar field Φ as

$$\mathcal{L}_{Z'\Phi\Phi} = ig_{Z'\Phi\Phi} Z'_\mu (\partial^\mu \Phi^* \Phi - \Phi^* \partial^\mu \Phi) \quad (22)$$

where $g_{Z'\Phi\Phi}$ is the corresponding coupling constant for the width of Z' boson decay into $\Phi\tilde{\Phi}$ pair we have the expression

$$\Gamma(Z' \rightarrow \Phi\tilde{\Phi}) = N_\Phi M_{Z'} \frac{g_{Z'\Phi\Phi}^2}{48\pi} \left(1 - \frac{4m_\Phi^2}{M_{Z'}^2}\right)^{3/2} \quad (23)$$

where N_Φ is the color factor ($N_{F_a} = 8$ for scalar gluons, $N_{S_a^{(\pm)}} = 3$ for scalar leptoquarks, $N_{\Phi'_a} = 1$ for the additional colorless scalar doublet) and m_Φ is a mass of the scalar particle.

The scalar gluons F_a and the scalar leptoquarks $S_a^{(\pm)}$ gives the main contribution into Z' boson width of type (23). The coupling constants of these particles with Z' boson are predicted by the MQLS model as

$$g_{Z'F_a F_a} = -\frac{e}{2} \frac{\sigma}{s_W c_W}, \quad g_{Z'S_a^{(\pm)} S_a^{(\pm)}} = -e \left(\frac{\sigma}{2s_W c_W} \pm \frac{2t_W}{3\sigma} \right) \quad (24)$$

where $t_W = \tan \theta_W$ and $\sigma = s_W s_S / \sqrt{1 - s_W^2 - s_S^2}$.

The partial widths of Z' decays into scalar gluon and scalar leptoquark pairs of type (23), (24) depend on parameter s_S and on masses of these scalar particles and on Z' mass $M_{Z'}$. The parameter s_S is defined by the mass scale $M_c \sim M_V$ of the four-color symmetry breaking and by the intermediate mass scale $M' \sim M_{Z'}$ [3,15]. For example for $M' \sim 10 \text{ TeV}$ and for $M_c = 10^4 \text{ TeV}, 10^6 \text{ TeV}, 10^8 \text{ TeV}$ we have $s_S^2 = 0.070, 0.112, 0.154$ respectively [15]. For numerical estimations we use below the value $s_S^2 = 0.114$ which corresponds to $M_{Z'} \sim 1 - 5 \text{ TeV}$ and $M_c \sim 10^3 \text{ TeV}$. The current mass limits for scalar leptoquarks are of about $m_{S^{(\pm)}} \gtrsim 250 - 300 \text{ GeV}$ in dependence on details of their interactions with fermions [4]. At the present time there are no reliable experimental mass limits for the scalar gluons but it is reasonable to expect their masses to be of the same order or slightly greater than the scalar leptoquark ones. Below in calculations we use for the masses of the scalar leptoquarks and of the scalar gluons the value 300 GeV. With these values of s_S^2 and of the masses of scalar particles the relative total width of Z' -boson $\Gamma_{Z'}/M_{Z'}$ occurs to be equal to

$$\Gamma_{Z'}/M_{Z'} = 4.3\% (1.1\%, 3.2\%), \quad 5.2\% (2.0\%, 3.2\%), \quad 5.3\% (2.1\%, 3.2\%) \quad (25)$$

for $M_{Z'}$ of about respectively 1 TeV, 3 TeV, 5 TeV and above, the corresponding values of the relative widths of the Z' decays respectively into scalar particles and into fermions are shown in parenthesis.

The computation of the cross sections (15) has been performed with using the set of parton distribution functions [22] in the leading order with the fixed flavor number scheme. The figure 1 shows the cross sections $\sigma_s(M_{Z'}, \Delta M)$ of $\mu^+\mu^-$ pair production at the LHC energy with account of Z' boson of the *MQLS* model in comparison with E_6 , *LRM* and *SSM* models as well as the background cross section $\sigma_{SM}(M_{Z'}, \Delta M)$ predicted in the SM (for the mass window of MQLS Z' boson). As seen the signal cross section in all the models (incuding the MQLS model) essentially exceeds the background one.

Comparing the results of the *MQLS*, E_6 , *LRM* and *SSM* models it should be noted that the *MQLS* model predicts the relatively large leptonic vector coupling constant $v_\mu^{Z_2} \sim -1.1$ and mainly due to this circumstance in the *MQLS* model the value of $I^{Z'Z'}(M, S)$ in (15) exceeds the corresponding values in E_6 , *LRM* and *SSM* models, which increases the *MQLSM* cross section. On the other hand the width of Z' boson in *MQLS* model with account of the scalar and fermionic decays is predicted to be larger than that in E_6 , *LRM* and *SSM* models (for example, at $M_{Z'} = 3 TeV$ we obtain $\Gamma_{Z'}/M_{Z'} = 5.2\%, 0.5\%, 2.1\%, 3.1\%$ in *MQLS*, E_6 , *LRM*, *SSM* models respectively), which decreases the *MQLSM* cross section due to decreasing the factor $P_{ij}(M^2)$. As a result as we see in the figure 1 the signal cross section in *MQLS* model still exceeds the prediction of E_6 model and approximately coincides with those in *LRM* and *SSM* models.

The figure 2 shows the integrated luminosity which is necessary for the observation of Z' boson of the *MQLS* model at 5σ significance ($\mathcal{S}' = 5$) in dependence on Z' mass in comparison with E_6 , *LRM* and *SSM* models. From the figure 2 and using also the formulas (15)–(20) we obtain that Z' boson of the *MQLS* model with masses

$$M_{Z'} < 2.44 \pm_{0.15}^{0.13} TeV, \quad M_{Z'} < 3.50 \pm_{0.29}^{0.22} TeV, \quad M_{Z'} < 4.67 \pm_{0.52}^{0.31} TeV \quad (26)$$

can be observed in $\mu^+\mu^-$ events at the LHC with 5σ significance at integrated luminosity $L = 1 fb^{-1}, 10 fb^{-1}, 100 fb^{-1}$ with expected numbers of signal (background) events $N_s(N_b) = 3.47(0.038), 3.45(0.036), 3.34(0.031)$ respectively. The unsertainties in (26) are caused by those in parton distribution functions.

Table 1: The upper Z' boson masses in *MQLS* model observable at the LHC in dependence on integrated luminosity L and on significance $\mathcal{S}'\sigma$ in comparison with E_6 , *LRM*, *SSM* models

L, fb^{-1}	<i>MQLSM</i>			E_6	LRM	SSM
	5σ	3σ	1σ	5σ	5σ	5σ
1	2.44	2.90	3.95	2.18	2.50	2.67
10	3.50	4.01	5.14	3.18	3.57	3.74
100	4.67	5.19	6.38	4.28	4.72	4.89

The central values in (26) and the corresponding values for 3σ and 1σ significancies in *MQLS* model are shown in the first columns of the Table 1. As seen the *MQLSM* Z' boson with masses

$$M_{Z'} < 5.2 TeV \quad (27)$$

can manifest itself in $\mu^+\mu^-$ events at the LHC at integrated luminosity $100 fb^{-1}$ with 3σ significance, while for

$$M_{Z'} > 6.4 TeV \quad (28)$$

its effect in $\mu^+\mu^-$ events will not exceed 1σ i.e. it will be practically invisible at the LHC.

For comparison with the *MQLS* model the last three columns of the Table 1 show the 5σ predictions of E_6 , *LRM*, *SSM* models. As seen the central values in (26) exceed the corresponding predictions of E_6 model and are near the predictions of *LRM* and are slightly below the predictions of *SSM* model. It is worthy to note that the *MQLSM* Z' boson has some specific features [10] which give the possibility in the case of observation of Z' boson to identify its origin.

In conclusion, we resume the results of the work.

The cross section of the $\mu^+\mu^-$ pair production in pp -collisions at the LHC is calculated and analysed with account of the Z' boson induced by the four color quark-lepton symmetry (*MQLS*). The corresponding $\mu^+\mu^-$ invariant mass spectrum with account of the Z' boson width is analysed in dependence on the Z' mass. The mass region for the *MQLS* Z' boson observable at the LHC is found in dependence on the significance and on the integrated luminosity. In particular, it is shown that the *MQLS* Z' boson can be observable at the LHC with 3σ significance at $L = 100 \text{ fb}^{-1}$ up to $M_{Z'} < 5.2 \text{ TeV}$. The results are discussed in comparison with predictions of E_6 , *LRM*, *SSM* models.

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Figure captions

Fig. 1. Cross section $\sigma_s(M_{Z'}, \Delta M)$ of $\mu^+\mu^-$ pair production at the LHC as a function of Z' boson mass $M_{Z'}$ in $MQLS$ model (solid line), in $E_6(\psi)$ model (dotted line), in LRM (dotdashed line) and in SSM (dashed line). The lower line indicate the SM cross section $\sigma_{SM}(M_{Z'}, \Delta M)$ for $MQLSM$ mass window ΔM . Gray filled area denotes the MQLSM cross section uncertainties resulted from the uncertainties in parton distribution functions.

Fig. 2. Integrated luminosity L needed for 5σ discovery of Z' boson at the LHC in dependence on Z' boson mass $M_{Z'}$ in $MQLS$ model (solid line), in $E_6(\psi)$ model (dotted line), in LRM (dotdashed line) and in SSM (dashed line). Gray filled area denotes the MQLSM luminosity uncertainties resulted from the uncertainties in parton distribution functions.

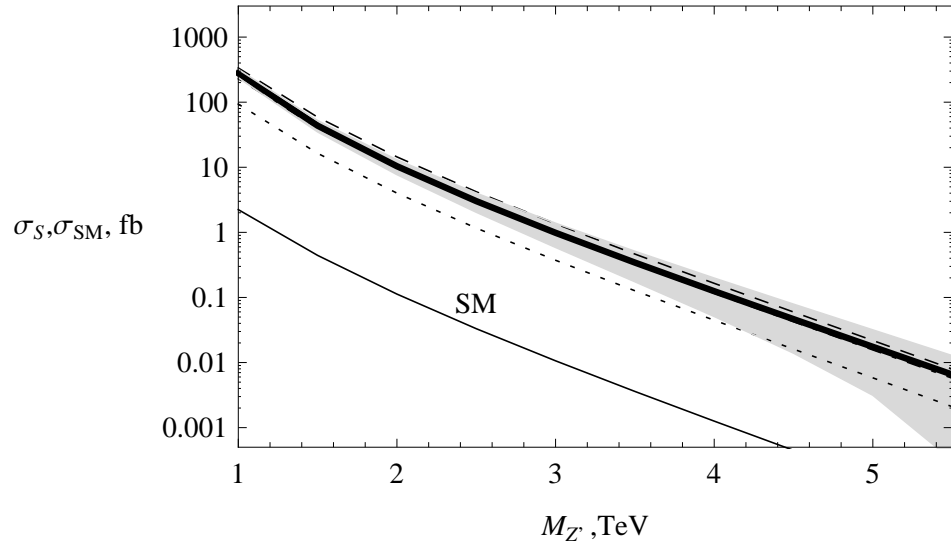


Figure 1:

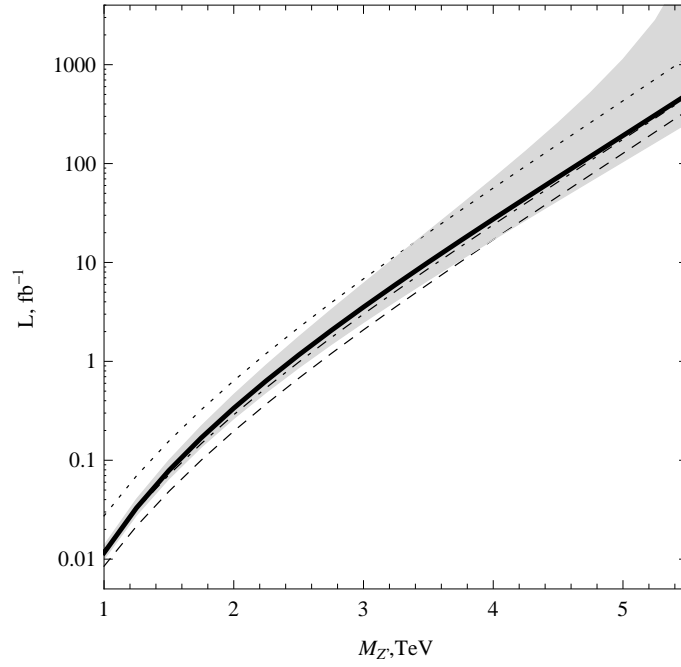


Figure 2: